# Search for Scalar Top and Scalar Bottom Quarks at the Tevatron

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*For the DØ and CDF collaborations*

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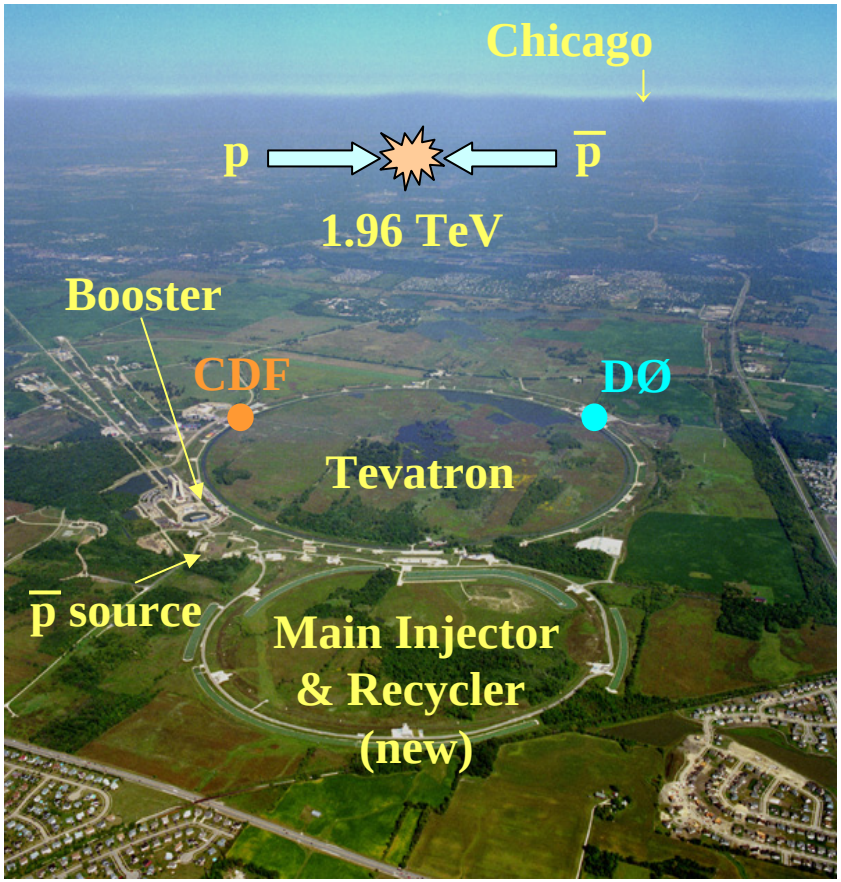
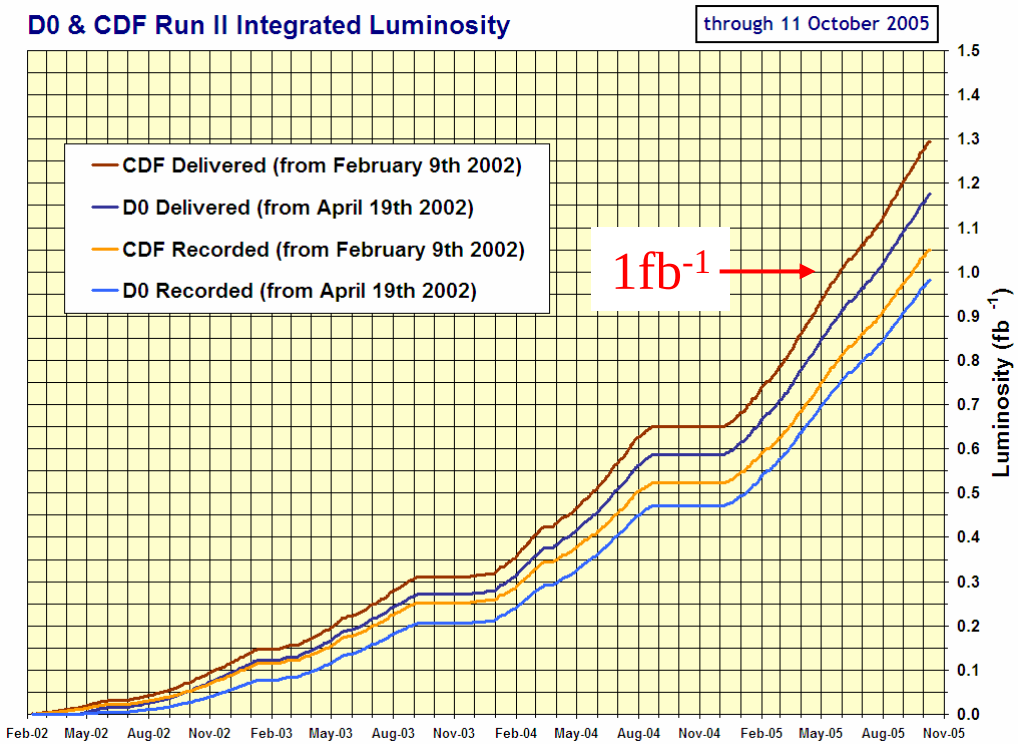
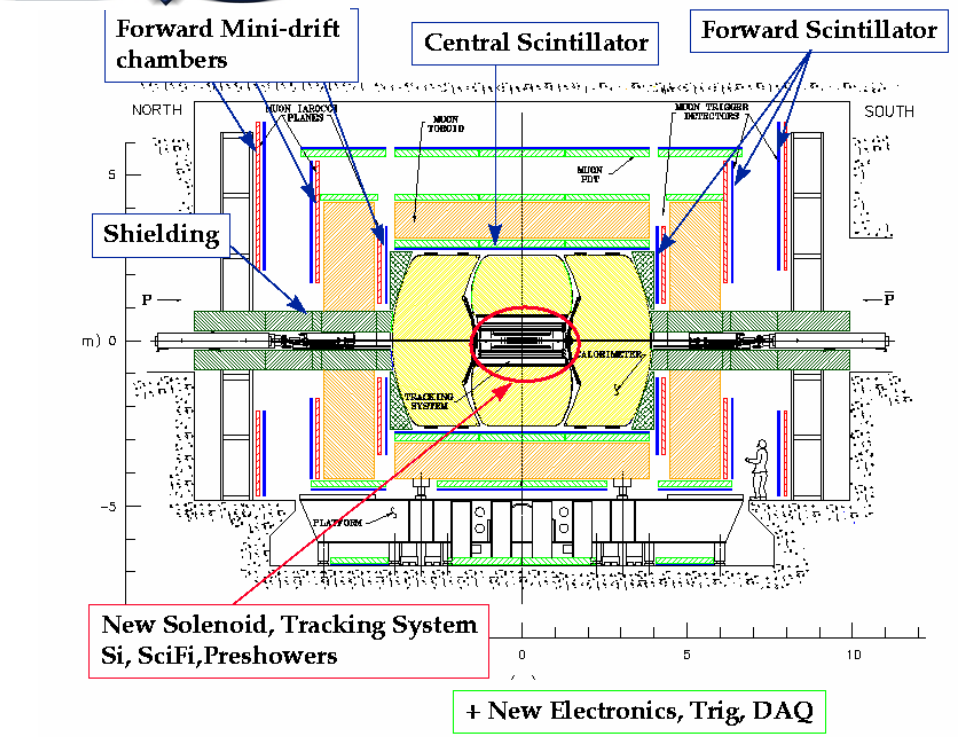
# Tevatron at Fermilab – Run II

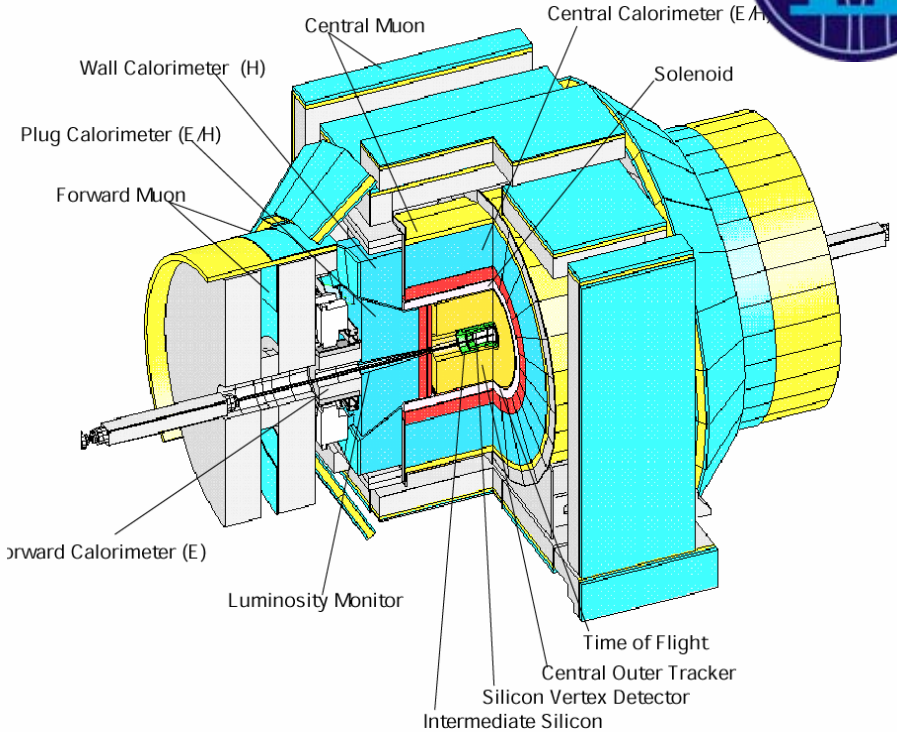



- Run II goal: 4 ~ 9 $fb^{-1}$ in 2009
- Analyses presented here use up to 340 $pb^{-1}$

# DØ and CDF Detectors



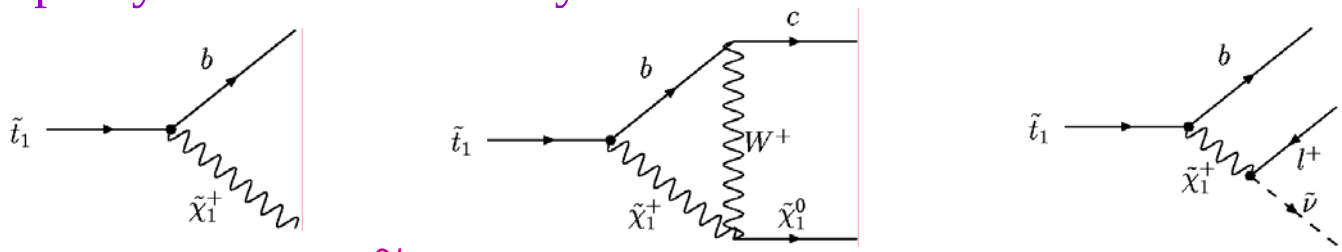

- Both general purpose detectors well understood and highly efficient
  - Precise tracking with silicon vertex detector
  - Excellent calorimeters and muon chambers coverage

# Scalar Top and Scalar Bottom

- Supersymmetry
  - SUSY overcomes some of the theoretical problems in the SM by introducing new degrees of freedom
  - Every SM particle has supersymmetric partners:
    - quarks/leptons ↔ 0-spin squarks/sleptons, gauge bosons ↔ ½-spin gauginos
  - R-parity: $R_p = (-1)^{3B+L+2S} = +1$ (SM) ; $= -1$ (SUSY)
    - If R-parity is conserved (RPC), the LSP is stable ⇒ a good dark matter candidate
    - Small violation of R-parity is not excluded (RPV) ⇒ additional couplings and the LSP decays into SM particles
- Stop and Sbottom (in generic MSSM model)
  - Large top mass ⇒ substantial mixing between SUSY partners of the L- and R-handed top quark; thus the lightest stop could be the lightest squark
  - Sbottom is also expected to be light at large tanβ
  - Stop/sbottom can be pair produced through gluon fusion and quark-antiquark annihilation at the Tevatron, and stop can decay in various modes

# Search Channels

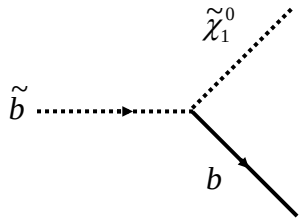
- Scalar top
  - R-parity conservation decay modes:




    - Decay channel $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ (on-shell chargino) is difficult to explore at the Tevatron due to the high chargino mass limit of LEP2
    - Decay channel $\tilde{t}_1 \to c\tilde{\chi}_1^0$ has been extensively explored, but it might not be the dominant decay for stop masses accessible at the Tevatron
    - 3-body decays via virtual chargino:
      - Decay channel $\tilde{t}_1 \to bl\tilde{\nu}$ is almost closed for most of the stop mass within the Tevatron reach, due to slepton mass limit of LEP2
      - Decay $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ dominates if the sneutrino mass is much greater than the $W$ mass, but it has very limited potential for the Tevatron
      - We explored decay channel $\tilde{t}_1 \to bl\tilde{\nu}$ which dominates if the sneutrino mass is of the same order as the $W$ mass. If $\tilde{\chi}_1^0$ is the LSP: $\tilde{\nu} \to \nu\tilde{\chi}_1^0$
  - R-parity violation decay modes: $\tilde{t}_1 \to b\tau$

# Search Channels

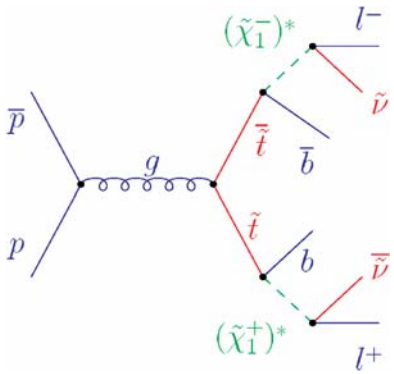
- Scalar bottom
  - Dominant decay mode: $\tilde{b}_1 \to b\tilde{\chi}_1^0$ (assuming $\tilde{\chi}_1^0$ is the LSP)




  - Direct production of sbottom pair, decaying into $\tilde{b}\bar{\tilde{b}} \to b\bar{b}\tilde{\chi}_1^0\bar{\tilde{\chi}}_1^0$
  - Sbottom quarks from gluino decays $\tilde{g} \to \bar{b}\tilde{b} \to \bar{b}b\tilde{\chi}_1^0$

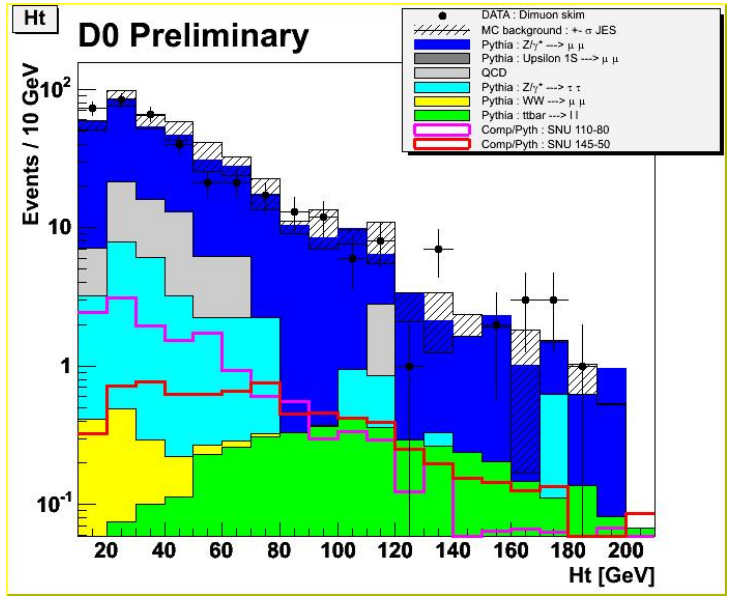
# Search for Stop: $\tilde{t}_1 \to b l \tilde{\nu}$

- Search in channel $\tilde{t}_1\bar{\tilde{t}}_1 \to b\bar{b}\,\mu^+\mu^-\tilde{\nu}\bar{\tilde{\nu}}$
- Integrated luminosity ($\mathcal{L}$) = 339 pb$^{-1}$
- Main background
  - $Z/\gamma^* \to \mu\mu$ / $\tau\tau$
  - QCD multi-jet
  - $\Upsilon(1S) \to \mu\mu$
  - *WW*
  - Top pair
- Selection
  - $p_T(\mu_1)$>8 GeV, $p_T(\mu_2)$>6 GeV
  - 2-dim. cut on $ME_T$, $\Delta\phi(\mu_1, ME_T)$ plane ($ME_T$>20-50 GeV)
  - At least 1 jet with $E_T$(j)>15 GeV
  - *b*-tag based on the impact parameter of the tracks in the jet
  - $m_{\mu\mu} \notin$[75,120] GeV for $ME_T$<50 GeV
- After cuts
  - Top pair dominates background (2.3 out of 2.9 events)
  - 1 event left in data (signal ~3 events)




- Use spectra of $H_T = \sum_{jets} |E_T|$ to discriminate between top and stop-signal

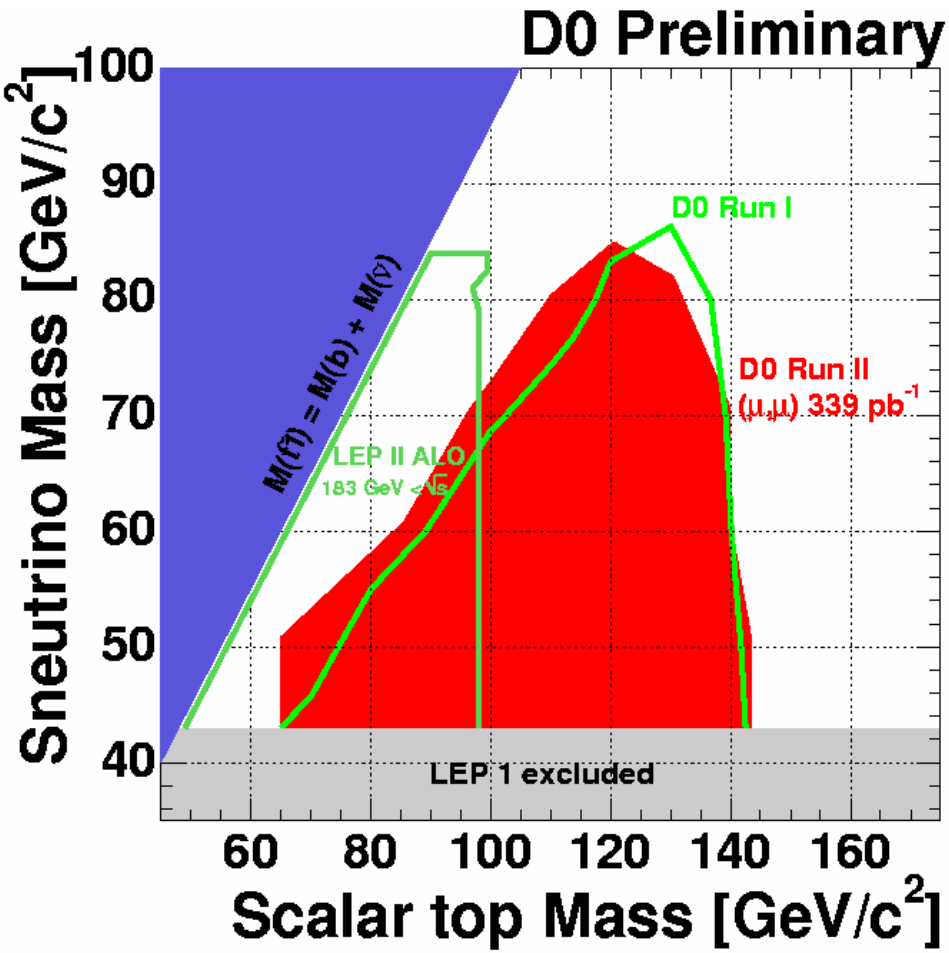
After pre-selection




| $H_T$ bin (GeV) | Background | Data |
|---|---|---|
| [0, 40] | 0.11 ± 0.03 | 0 |
| [40, 80] | 0.89 ± 0.43 | 0 |
| [80, 120] | 0.75 ± 0.13 | 0 |
| [120, 160] | 0.56 ± 0.07 | 1 |
| > 160 | 0.57 ± 0.08 | 0 |

# Search for Stop: $\tilde{t}_1 \to bl\tilde{\nu}$

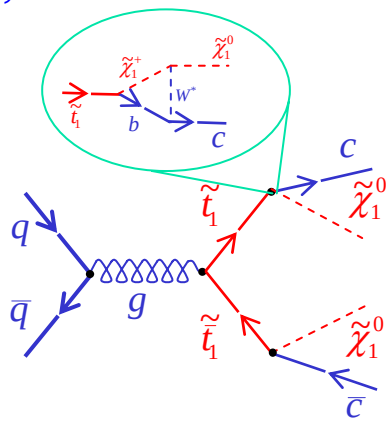
- Obtain exclusion limits assuming $BR(\tilde{t}_1 \to bl\tilde{\nu}) = 100\%$ and equal *BR* in three lepton flavors
- Improvement w.r.t. Run I in low $\Delta m$(stop, sneutrino) region due to low $p_T(\mu)$ requirement
- Preferred channel: eμ (+jets) – 2×*BR*, much lower *Z*/Drell-Yan background – expect significant improvement by new analysis in eμ channel



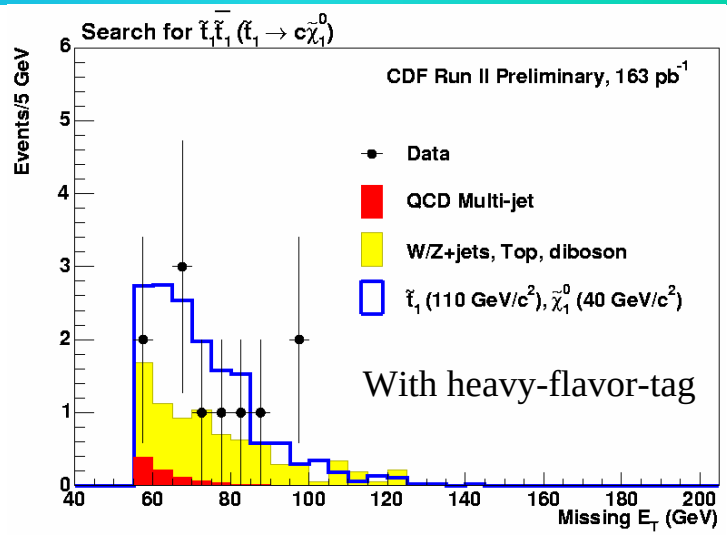

95% CL excluded region. Also shown is DØ Run I result with 108 pb$^{-1}$ luminosity in the eμ final state.

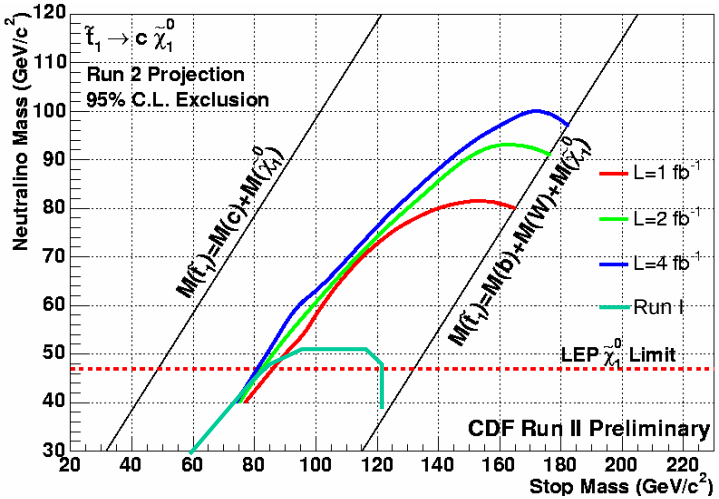
# Search for Stop: $\tilde{t}_1 \to c\tilde{\chi}_1^0$

- Assume $\tilde{\chi}_1^0$ is the stable LSP, and $BR(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 100\%$
- $\mathcal{L}$ = 163 pb$^{-1}$
- Background
  - QCD multi-jet
  - *W*/*Z*+jets, top, di-boson
- Selection
  - $E_T(j_1)$>35 GeV, $E_T(j_2)$>25 GeV
  - $ME_T$ > 55 GeV
  - No isolated lepton (e, μ), veto τ
  - Heavy-flavor-tagging on one charm jet (based on track impact parameter)
- Result
  - Upper cross section limits, but no additional exclusion in mass plane




| Heavy-flavor-tag | No | Yes |
|---|---|---|
| Background | 105 ± 12 | 8.3 ± 2.3 |
| Data | 119 | 11 |

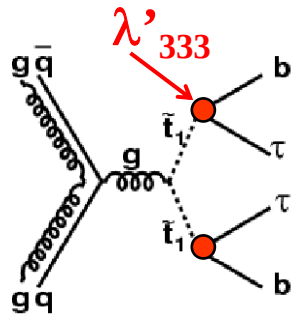


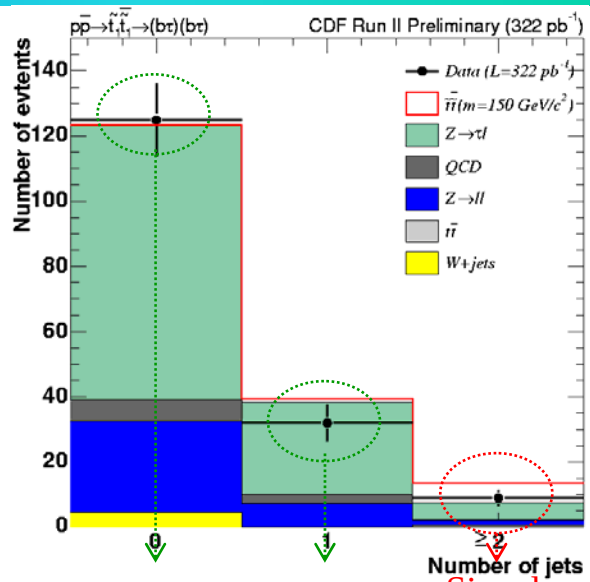

CDF Run II projections based on integrated luminosity = 1, 2, 4 fb$^{-1}$

# Search for Stop (RPV): $\tilde{t}_1 \to b\tau$

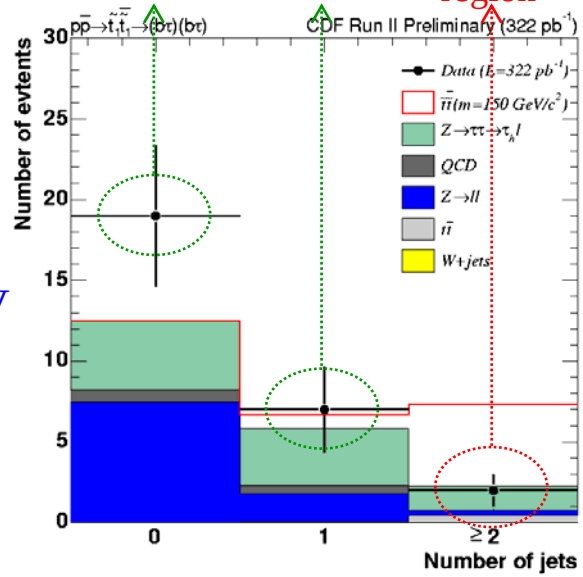
- Search channel $\tilde{t}_1\bar{\tilde{t}}_1 \to b\bar{b}\,\tau_{lep}\tau_{had}$
- $\mathcal{L}$ = 332 pb$^{-1}$
- Background
  - QCD
  - *W*/*Z* + jets
  - Top, di-boson
- Selection
  - 1 lepton (e, μ) $p_T(l) > 10$ GeV (from $\tau_{lep}$)
  - 1 $\tau_{had}$ $p_T(\tau) > 15$ GeV
  - At least 2 jets $E_T(j) > 20$ GeV
  - Veto *Z*, veto *W* ($m_T(l, ME_T) < 35$ GeV)
  - Final cut $S_T = p_T(l) + p_T(\tau) + ME_T > 110$ GeV
- Result
  - $N_{jet} = 0, 1$ are control regions, $N_{jet} \geq 2$ is signal region




Loose cut
$S_T > 80$ GeV



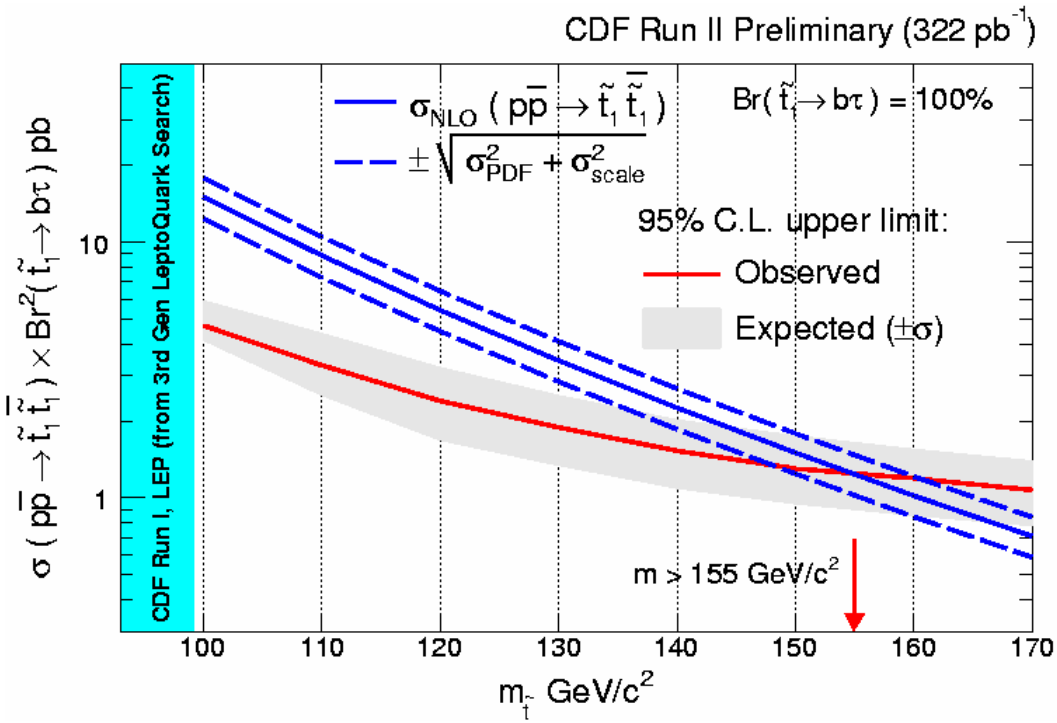

Final cut
$S_T > 110$ GeV




| (Signal region) | e + τ | μ + τ | Sum |
|---|---|---|---|
| Background | 1.27 ±0.29 | 0.99 ±0.35 | 2.26 ±0.46 |
| Data | 1 | 1 | 2 |

# Search for Stop (RPV): $\tilde{t}_1 \to b\tau$

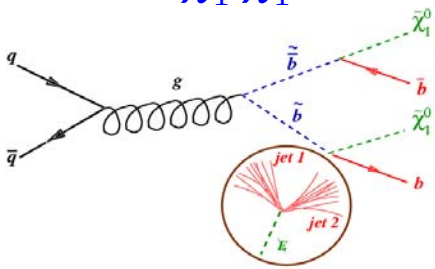
- Obtain limits assuming
  $BR(\tilde{t}_1 \to b\tau) = 100\%$
- Stop mass limit
  - $m_{stop} > 155$ GeV (nominal)
  - $m_{stop} > 151$ GeV (conservative)
- Since the stop pair production process is very similar to the pair production of the third generation scalar leptoquark ($LQ_3$)
  $p\bar{p} \to LQ_3\overline{LQ_3} \to b\bar{b}\,\tau\tau$
  and their NLO cross sections are very close to each other, the same mass limit is applicable to $LQ_3$



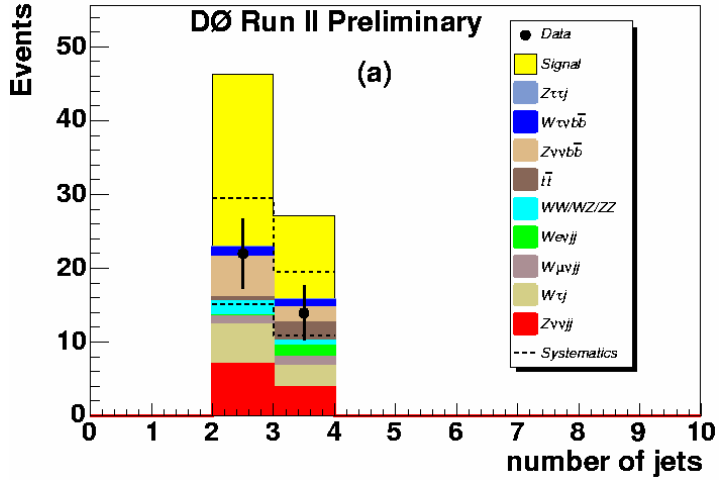

CDF Run I: $m_{stop} > 122$ GeV ($\mathcal{L} = 106$ pb$^{-1}$)

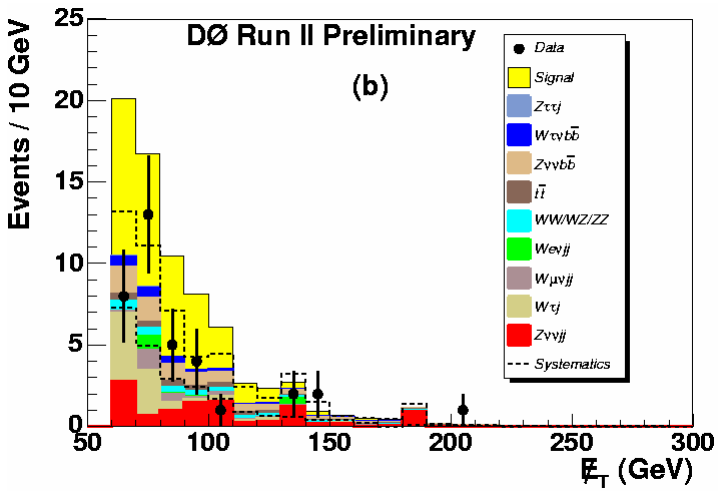
# Search for Sbottom (Direct Production)

- Search channel $\tilde{b}\bar{\tilde{b}} \rightarrow b\bar{b}\tilde{\chi}_1^0\bar{\tilde{\chi}}_1^0$
- $\mathcal{L}$ = 310 pb$^{-1}$
- Background
  - *W*/*Z* + jets
  - Top, di-boson
  - QCD vanishes at large $ME_T$
- Selection
  - 2 jets acoplanar (3rd jet allowed), $ME_T$
  - Veto events with isolated e, μ, track (τ)
  - Single *b*-tag
  - Optimized cuts depending on sbottom mass: $E_T(j_1)$ > 40-70 GeV, $E_T(j_2)$ > 15-40 GeV, $ME_T$ > 60-100 GeV




| Cuts | Before *b*-tag | Opt. low | Opt. med. | Opt. high |
|---|---|---|---|---|
| Background | 1335 ± 48 | 38.6 ± 2.8 | 19.6 ± 1.7 | 4.40 ± 0.44 |
| Data | 1433 | 36 | 15 | 2 |
| Signal for $(m_{\tilde{b}}, m_{\tilde{\chi}_1^0})GeV$ | 68.8 ± 2.3 (140, 80) | 35.0 ± 1.2 (140, 80) | 21.6 ± 0.7 (160, 75) | 6.10 ± 0.17 (205, 60) |

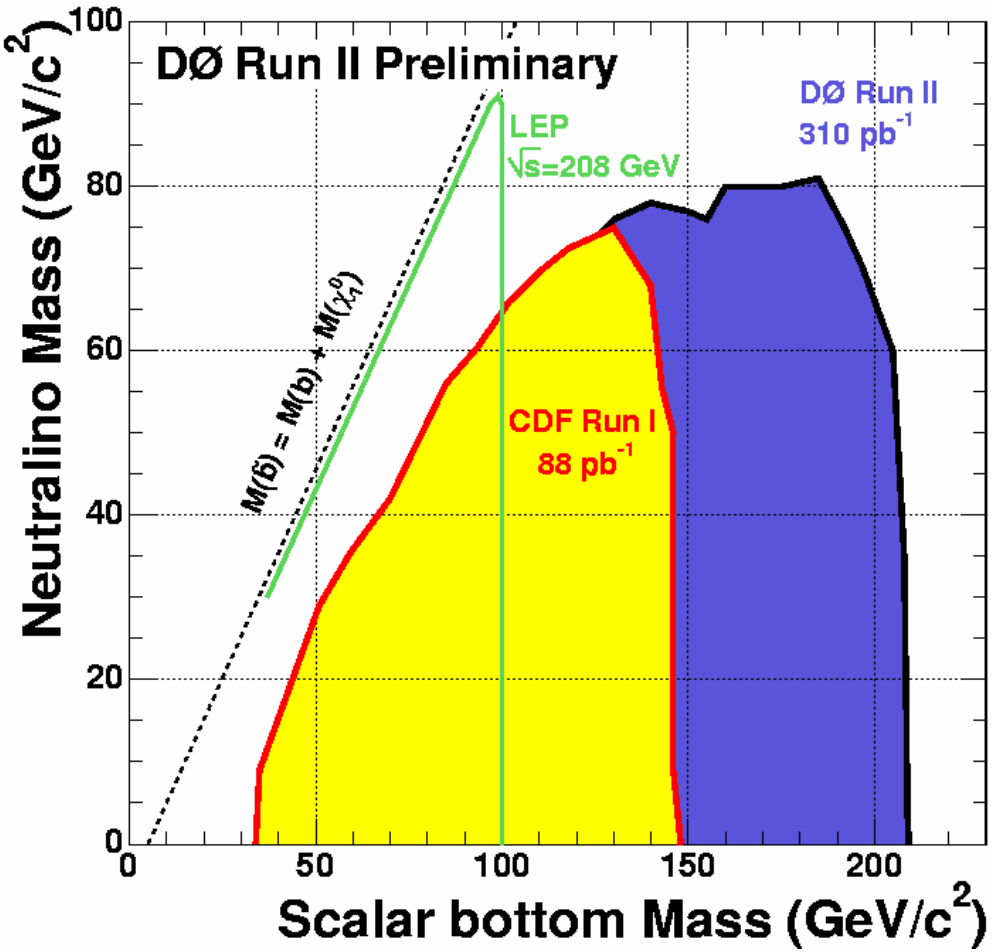



After *b*-tag, optimized cuts low set

# Search for Sbottom (Direct Production)

- Obtain exclusion limits assuming $BR(\tilde{b} \rightarrow b\tilde{\chi}_1^0) = 100\%$
- Significant improvement compared to the previous measurements
- Future improvement: double *b*-tag, better Jet Energy Scale and optimization of $E_T(j)$, $ME_T$ cuts

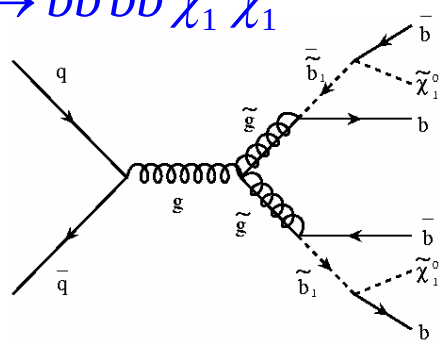



95% CL exclusion contour

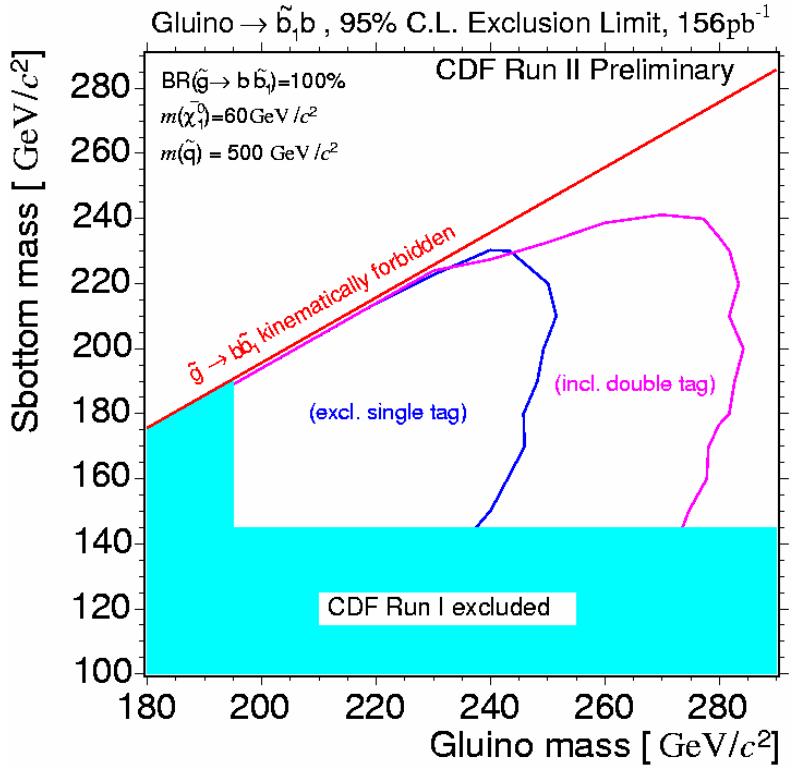
# Search for Sbottom (from Gluino Decay)

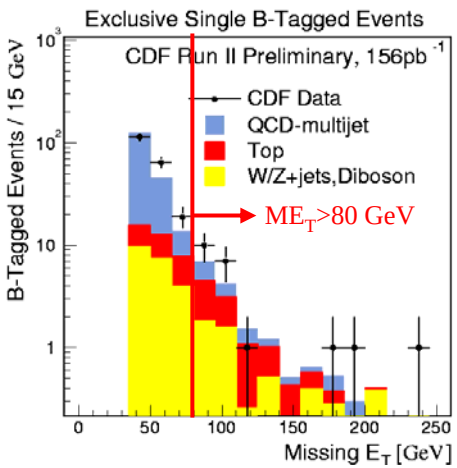
- Channel $\tilde{g}\tilde{g} \to \tilde{b}\bar{\tilde{b}}\,b\bar{b} \to b\bar{b}\,b\bar{b}\,\tilde{\chi}_1^0\,\bar{\tilde{\chi}}_1^0$

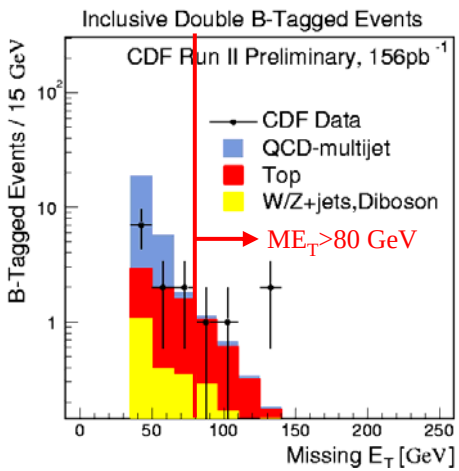
  $BR(\tilde{g} \to \tilde{b}\,b) = 100\%$
- $\mathcal{L} = 156\ \text{pb}^{-1}$
- Background
  - QCD multi-jet, $b\bar{b}$
  - $W/Z$+jets, top, di-boson
- Selection
  - At least 3 jets $E_T(j) > 15$ GeV
  - $ME_T > 80$ GeV
  - Angular cuts between jets and $ME_T$
  - Veto leptons (e, μ, τ)
  - One or more jets *b*-tagged




| # *b*-tag | $N_{b\text{-tag}} = 1$ | $N_{b\text{-tag}} \geq 2$ |
|---|---|---|
| Background | $16.4 \pm 3.7$ | $2.6 \pm 0.7$ |
| Data | 21 | 4 |




95% CL exclusion, mass limit set up to:

$m(\tilde{g}) > 280GeV, m(\tilde{b}) > 240GeV$

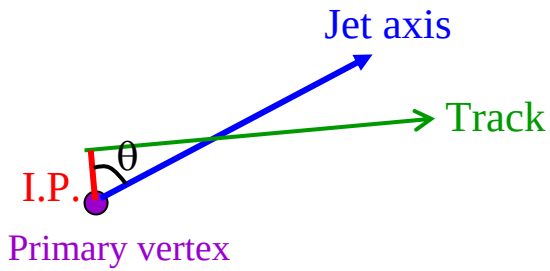
# Conclusions

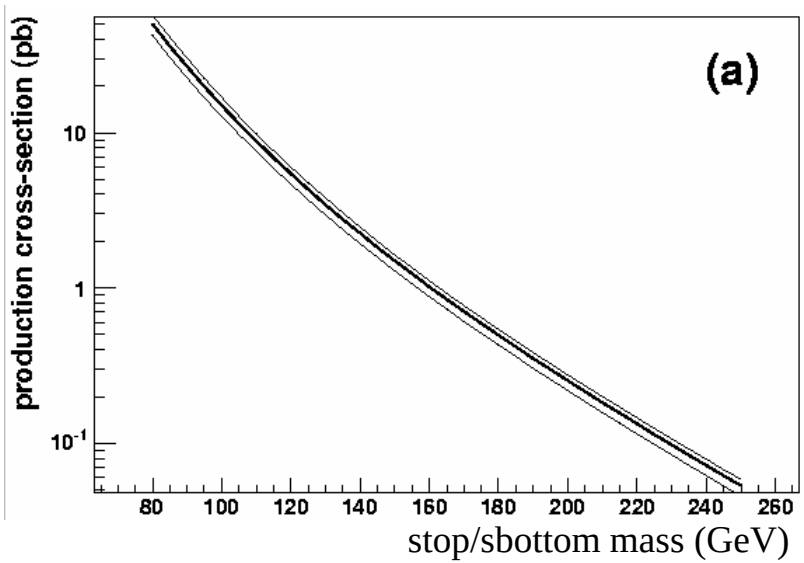
- DØ and CDF have searched for scalar top and scalar bottom quarks in various channels, using integrated luminosity of up to 340 $pb^{-1}$
  - Assuming one dominating decay channel and interpreting exclusion in terms of masses of stop/sbottom and decay products
- In some channels, substantial improvement over Run I results and extension of LEP excluded regions.
  - Especially in RPV stop search and in sbottom searches
- We are now analyzing the 1$fb^{-1}$ data, hoping for a discovery; otherwise there will be substantial improvement of the limits

# Backup

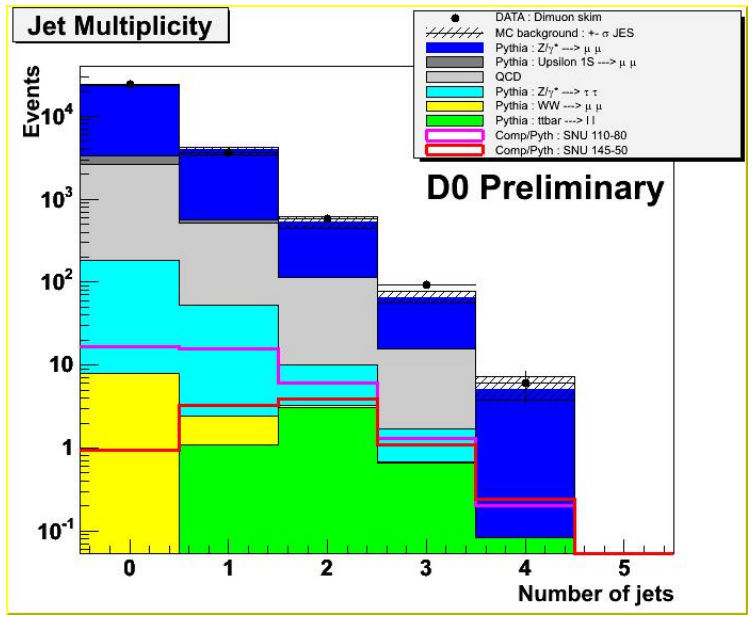
# Backup

- DØ *b*-tagging – Jet lifetime probability (JLIP)
  - Use the signed impact parameter significance of tracks associated to a jet ($\Delta R<0.5$ cone matching) to identify jets with long lived particles (mostly *b*-jets)
- DØ: stop → *b* + $\mu$ + sneutrino



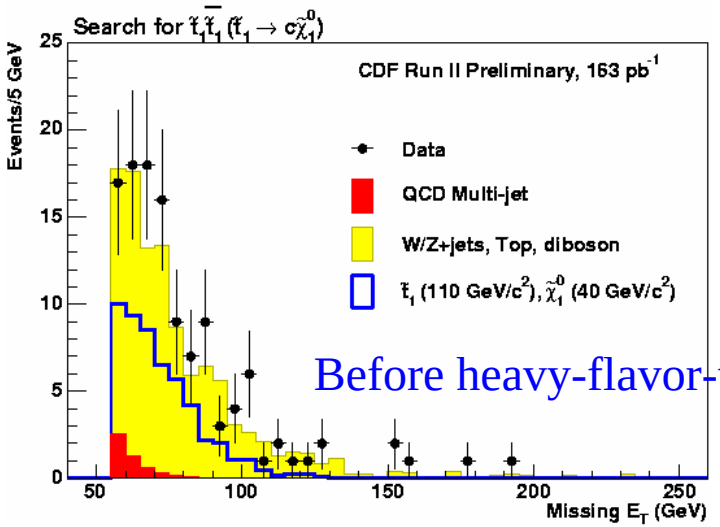




After pre-selection

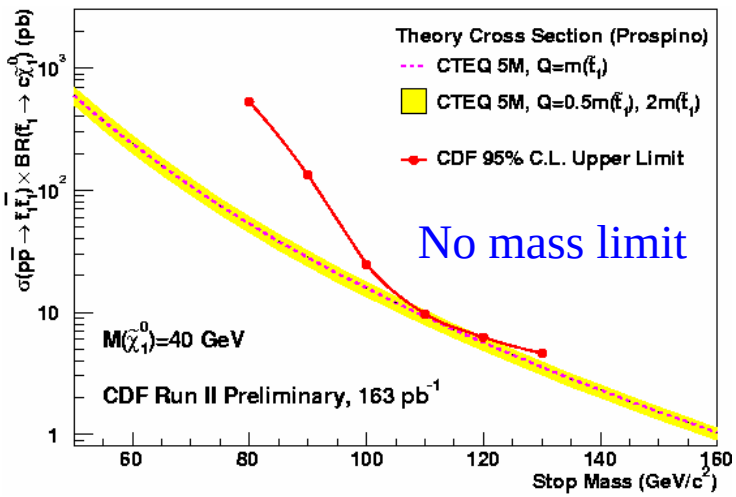


# Backup

- CDF: stop → *c* + neutralino

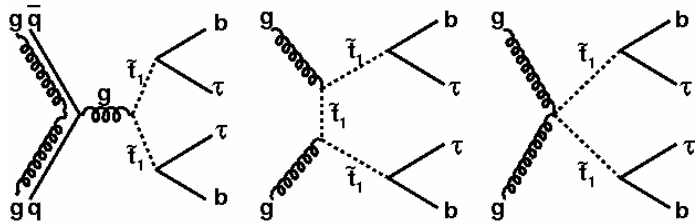


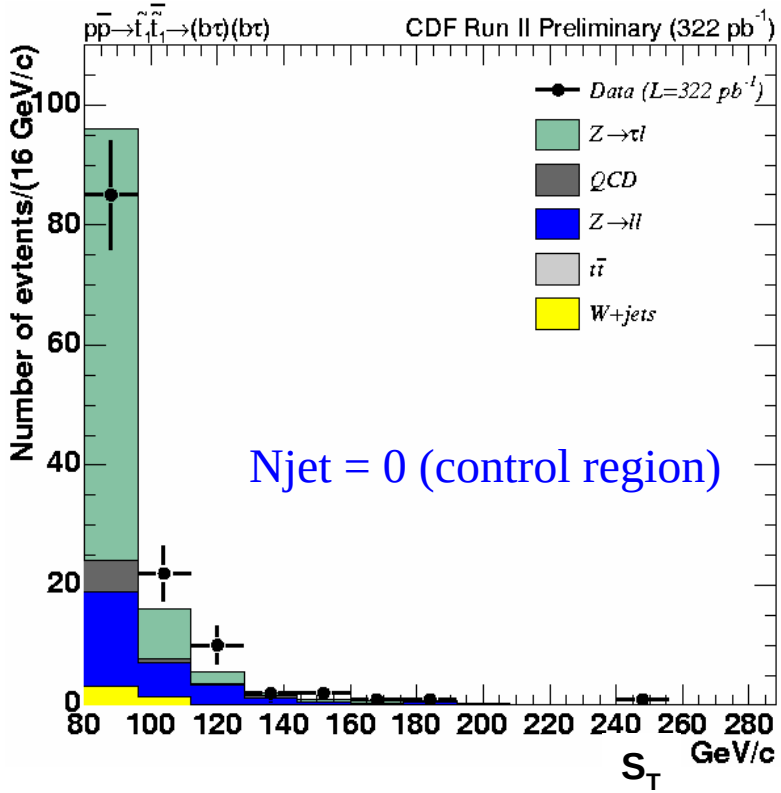

Before heavy-flavor-tag




No mass limit

- CDF RPV: stop → *b* + $\tau$

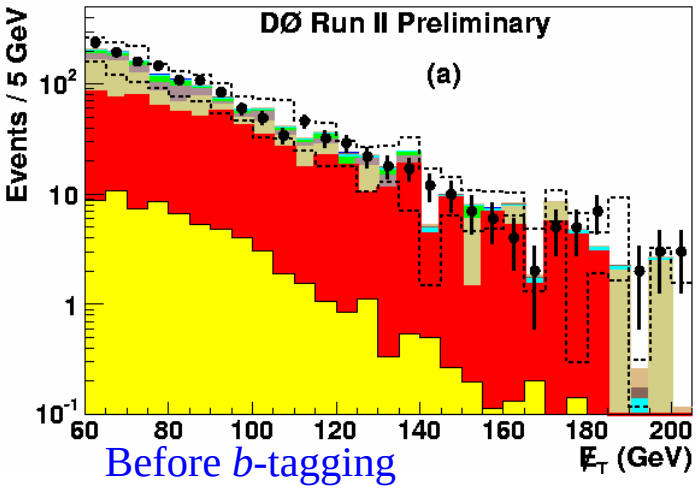


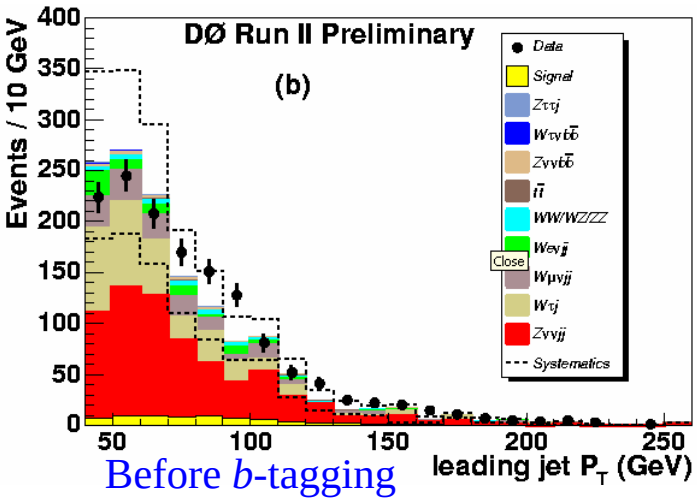

Njet = 0 (control region)

# Backup

- DØ: sbottom direct production




Before *b*-tagging




Before *b*-tagging

- CDF: sbottom from gluino decay

Control region (≥1 lepton) for cross check